Experimental and numerical studies for parameters identification of direct current motor

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ABSTRACT

Direct current (DC) motors are widely used in many applications especially those require a speed control, direction and closed-loop control system. In electric vehicle drive system, DC motor is commonly used for the propulsion of low power (<250 W) electric bicycle (e-bike) because it can operate directly from rechargeable batteries with a smart controller. In driving an e-bike in a closed loop control system, it is important to identify and estimate the dynamic of electrical and mechanical parameters. In this paper, the parameters such as armature resistance, armature inductance, back emf constant, torque constant, moment of inertia and viscous friction coefficient are ideally identified using dynamic responses experiments and tests focusing on no load motor and transient input tests. The motor is then modeled in MATLAB/Simulink using the identified motor parameters and its open loop speed and current responses are studied.

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1. INTRODUCTION

One of the major components of an e-bike system is the electric motor. The selection of motors for e-bikes may come from brushed permanent magnet direct current motor (PMDC), brushless direct current motor (BLDC), AC induction motor or permanent magnet synchronous motor (PMSM) [1]. With the current technology, BLDC has become popular choice for designers since it is quiet, small in size, lighter and need less maintenance [2], [3]. However, not all designers prefer with BLDC and they are more likely tend to use brushed motors especially for those focusing on low power e-bike [4]. Brushed PMDC motor is more robust and reliable, relatively cheaper in terms of cost, use less power when in riding mode, easy to maintain and do not require frequent services [1], [3]. It is also lighter and smaller than other motors, has a great efficiency due to no field winding losses and ideal for control applications because of the linearity of its torque-speed relationship. These are the reasons why PMDC motor is popularly selected for the traction of low power e-bike.

In order to propel an e-bike, the correct controller with optimum performance is required [5]. Designers often use several types of closed loop controller technique including proportional integral derivative (PID), fuzzy or neural network controllers to make the system robust and reliable, thus improving the system performance during dynamic and steady state operation [1], [4]. To design such a good controller, motor parameters play an important role and they need to be addressed properly. Accurate modelling of PMDC motor with accurate motor parameters will help to predict and to understand better the linear and nonlinear characteristics of PMDC motor [6]. There are six parameters to be identified, which are armature resistance R_a, armature inductance L_a, back-emf constant K_e, torque constant K_t, moment of inertia J and viscous friction coefficient D_w. The model of direct current (DC) motor is developed in MATLAB/Simulink in section 2.

In this paper, the electrical and mechanical parameters of DC motor are identified using dynamic responses experiments and tests focusing on no load motor and transient input tests in section 3. In section 4, the results of speed and current responses between simulation and experimental are demonstrated. The paper will be concluded in section 5.

2. MODELING DESCRIPTION

2.1. Modeling of PMDC motor

A PMDC motor can be represented by electrical and mechanical part as shown in Figure 1. The equivalent circuit of electrical part consists of an armature resistance R_a, armature inductance L_a and back electromotive force E, while the motor developed torque T_m, rotor moment of inertia J, viscous friction D and load torque T_L represent the mechanical part [7].

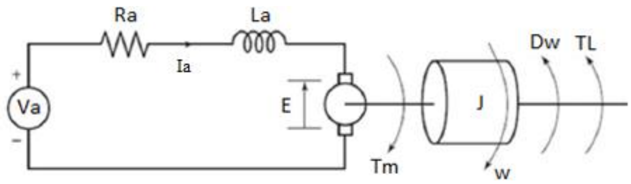


Figure 1. PMDC motor equivalent circuit

When a DC voltage V_a is applied to the circuit, the armature current I_a flows through the series armature resistance and armature inductance. The voltage will be generated across the armature winding which oppose the flow of armature current. The voltage produced across the armature is known as counter or back emf voltage E [8]. The back emf, E is associated with the rotational speed ω by a back emf constant K_e. The motor torque T_m is directly proportional to armature current I_a, by a torque constant K_t as (1) and (2).

$$E = K_e\omega \quad (1)$$

$$T_m = K_t I_a \quad (2)$$

The dynamic equations in time domain of the PMDC motor can be obtained by applying Kirchhoff's voltage law (KVL) and applying Newton’s law [9]. Using KVL to produce electrical equation referring to circuit in Figure 1.

$$I_a = \frac{1}{L_a}\int (V_a - I_a R_a - K_e\omega)dt \quad (3)$$

Applying Newton’s law to produce mechanical equation referring to Figure 1.

$$\omega = \frac{1}{J}\int (K_t I_a - D\omega - T_L)dt \quad (4)$$

The above equations can also be written in matrix form as shown in (5) [10], [11].

$$\begin{bmatrix} \frac{d}{dt} I_a \\ \frac{d}{dt}\omega \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_e}{L_a} \\ \frac{K_t}{J} & -\frac{D}{J} \end{bmatrix} \begin{bmatrix} I_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -\frac{1}{J} \end{bmatrix} \begin{bmatrix} V_a \\ T_L \end{bmatrix} \quad (5)$$

The relationship between the output and the input of a system with differential equations can be easily translated into algebraic equation in frequency domain by using laplace transform [12]. The equations in (3) and (4) can be solved simultaneously by taking rotational speed ω and armature current I_a as outputs while the inputs are DC voltage V_a and load torque T_L. Using Laplace Transform, these equations can be expressed as (6) and (7).

$$I_a(s) = \frac{V_a(s) - K_e\omega(s)}{sL_a + R_a} \quad (6)$$

$$\omega(s) = \frac{K_t I_a(s) - T_L(s)}{sJ + D} \quad (7)$$

Based on (6) and (7), PMDC motor can be simply modelled in MATLAB/Simulink. The dynamic model representation of e-bike PMDC motor from Laplace transform can be obtained as shown in Figure 2. The armature current is equal to $1/(sL_a+R_a)$ multiplied by the sum of armature voltage and back-emf constant feedback. On the other hand, the rotational speed is equal to 1/(sJ+D) multiplied by the sum of motor torque (product of armature current and contant torque) and load torque.

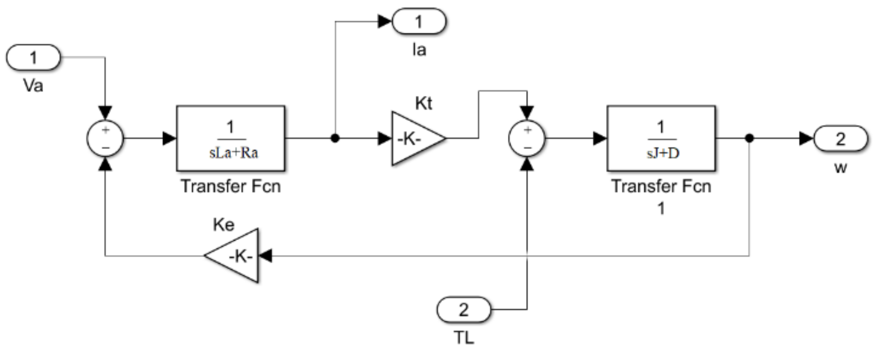


Figure 2. PMDC motor model in Simulink

2.2. Model specifications

The performance characteristics and capabilities of an e-bike motor rely on its specification. Each PMDC motor is manufactured with its own specification details and the details about the motor is given in the motor name plate [3], [12]. However, the details in the motor name plate do not specify all the necessary information needed by designers. It only mentions some standard parameters about the motor type and size, rated output power, rated speed, rated voltage and armature current. The motor used in the experiment has the nominal characteristics printed on its nameplate as presented in Table 1.

Table 1. The nominal values of PMDC motor at full load

No.	Characteristic	Value
1	Rated output power, P_m	350 W
2	Rated armature voltage, V_a	24 V
3	Rated speed, N	2750 rpm
4	Rated current, I_a	19.2 A

From the values given in Table 1, some parameters like armature resistance, back emf constant and torque constant are possible to be determined directly from the manufacturer's data using dynamic response equations. These parameters are directly calculated from the nominal values of PMDC motor and they are presented in Table 2. Therefore, they are not accurately representing the actual motor parameters but could be a quick reference for designers [13]. Some other important parameters like armature inductance, moment of inertia and viscous friction coefficient cannot be calculated directly because of the nonlinear characteristics of the motor. To find the rotational speed of the motor in rad/s [11].

$$\omega = \frac{2\pi n}{60} \quad (8)$$

The torque generated by the motor is directly proportional to armature current as in (2). The torque is also related to the output power by the rotational speed of the motor. The motor torque is a very important parameter to establish the running characteristics of DC motor.

$$T_m = \frac{P_m}{\omega} \quad (9)$$

Table 2. Calculated parameters of PMDC motor at full load

No.	Paramater	Value
1	Rotational speed, ω	287.98 rad/s
2	Motor developed torque, T_m	1.215 Nm
3	Torque constant, K_t	0.0633 Nm/A
4	Back EMF constant, K_e	0.0633 V/rad/s
5	Armature resistance, R_a	0.3 Ω
6	Back Emf voltage, E	18.23 V

3. RESEARCH METHOD

A digital oscilloscope, DC power supply units, voltage sensor, current sensor and an optical encoder along with a microcontroller board were used for data collection and monitoring in an experiment setup as shown in Figure 3. The setup used a regulated GW Instek GPC3060D DC power supply, Agilent N2791A voltage probe, Tektronix A622 current probe and Tektronix MD03024 oscilloscope. The microcontroller is programmed to display the motor speed in rpm.

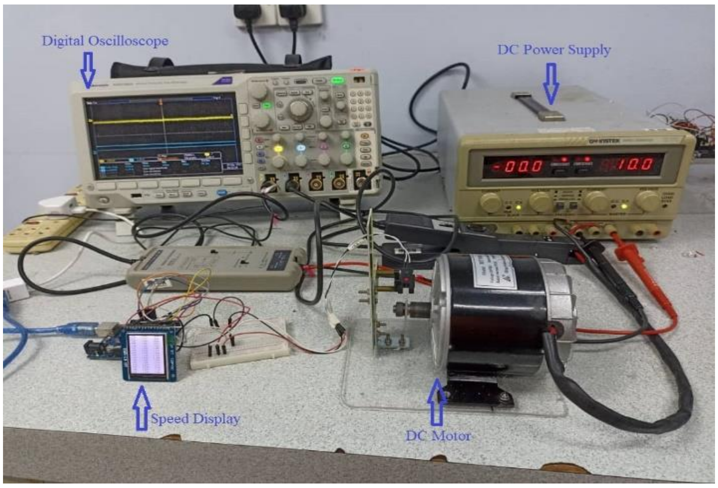


Figure 3. Experimental setup of PMDC motor

The PMDC motor's electrical and mechanical parameters were identified from a series of experimental setup to analyze the linear and nonlinear model of the system. The setup was using dynamic responses experiments and tests focusing on no load motor and transient input tests as discussed below. Experimental results are presented and demonstrated to identifiy correct parameters of PMDC motor.

3.1. Identification of armature resistance R_a and armature inductance L_a

The first and simplest parameter to be identified is armature resistance that can be measured directly using a digital multimeter between the motor terminal cables [14]. It is important to measure the resistance at different rotor position as listed in Table 3 because the resistance between the commutators and the carbon brushes inside the motor has small variations. The average armature resistance of PMDC motor is found to be 1.375 Ω. The calculated value of R_a by manufacturer in Table 2 has significant difference compared to the average value identified from experiment because it is directly calculated from nameplate at full load and do not accurate. At no load condition, the motor speed will be higher and the armature current produced is lower as shown in Table 4. Consequently, from Table 4, the armature resistance value also can be calculated as 1.286 Ω at V_a = 24 V which is close to the identified average value of 1.375 Ω.

The next parameter to be identified is armature inductance. A simple way to do this is by measuring the value using digital RLC meter at 1 kHz repeatedly [15], [16]. Taking the similar technique used in measuring armature resistance, the armature inductance value is identified at different rotor position as shown below. The values of several armature inductances of PMDC motor should be averaged and found to be 298.75 uH.

Table 3. R_a and L_a values at different rotor position

Rotor position angle (Degree)	R_a (Ω)	L_a (uH)
10	1.2	300
45	1.5	300
90	1.8	291
135	1.5	300
180	1.1	302
225	1.4	298
270	1.1	302
315	1.4	297

3.2. Identification of back EMF constant K_e and torque constant K_t

To measure the motor back-emf constant, the PMDC motor was tested under no load steady-state condition and an open-loop speed response can be analyzed. As the back emf voltage is proportional to an angular speed of the motor, the back emf constant can be accurately identified directly by taking several readings at different armature voltages [16], [17]. A steady-state DC input voltage is applied from 2 V to 24 V to the motor and a list of recorded values are tabulated in Table 4.

Table 4. No load test result of DC motor

V_a (V)	I_a (A)	n (rpm)	ω (rad/s)	E (V)	P_m (W)	T_m (Nm)
2	0.35	223	23.35	1.52	0.53	0.0228
4	0.42	508	53.19	3.42	1.44	0.0270
6	0.47	789	82.61	5.35	2.52	0.0305
8	0.52	1071	112.13	7.29	3.79	0.0338
10	0.56	1363	142.71	9.23	5.17	0.0362
12	0.60	1621	169.72	11.2	6.71	0.0395
14	0.63	1975	206.78	13.1	8.27	0.0400
16	0.65	2142	224.27	15.1	9.82	0.0438
18	0.67	2500	261.75	17.1	11.44	0.0437
20	0.68	2757	288.66	19.1	12.96	0.0449
22	0.70	3057	320.07	21.0	14.73	0.0460
24	0.72	3329	348.55	23.0	16.57	0.0475

The armature current and the motor speed were measured to calculate the back emf. The mechanical power P_m was calculated by multiplying back emf voltage voltage with armature current and the motor developed torque T_m values are obtained by using (9). The back emf constant K_e is actually represented by a slope of a linear graph between back emf voltage and motor speed as illustrated in Figure 4. In many situations, torque constant is numerically equal to back emf constant when SI units are used. The law of conservation of energy says that the input electrical power must be equal to the output mechanical power plus the motor electrical losses.

$$I_a^2 R_a + K_e I_a \omega = K_t I_a \omega + I_a^2 R_a \tag{10}$$

Using the tabulated data in Table 4, the motor electrical torque against armature current response is plotted as depicted in Figure 5. Theoretically these characteristics should be straight line by (2). The slope of this linear graph determines the torque constant of the motor K_t. The measured values between K_e and K_t are not so much different.

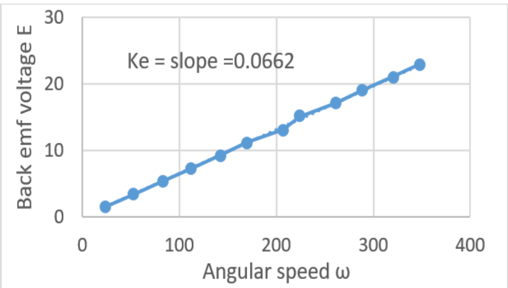


Figure 4. Back emf voltage versus angular speed

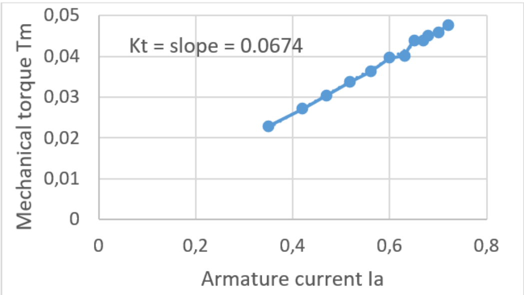


Figure 5. Mechanical torque versus armature current

3.3. Identification of viscous friction coeficient D

PMDC motor mechanical loss due to friction is very small and sometime negligible. However, it plays an important role in determining motor efficiency and should be considered in the control system design associated with closed loop systems [18], [19]. One of the mechanical parameters is viscous friction coefficient which is based on basic Newton's motion equation of motor using (4). Under steady-state condition, when there are no speed change and no-load torque considered, the viscous friction coefficient was identified from the linear slope of the response between motor torque and angular speed as illustrated in Figure 6.

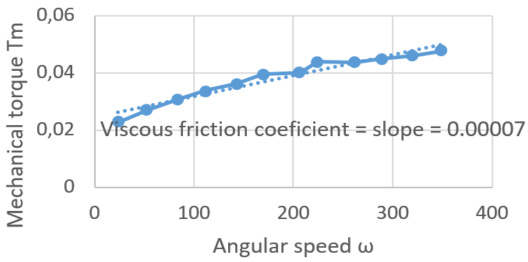


Figure 6. Mechanical torque versus angular speed

3.4. Identification of moment of inertia J

The method used to identify the moment of inertia is through a test known as retardation test [20], [21]. In this test, the PMDC motor was run at a speed just above the rated speed of the motor. Then the supply to the motor was cut off and the motor speed was slowed down until it finally stops. The output power P_m to the motor before cutting off the supply was recorded as 24.52 W. During this test, time for speed fall was recorded and the relationship between the motor speed in rpm and time is presented in Table 5. The sampling time for each speed is 600 ms.

Table 5. Result of motor retardation test

t (ms)	n (rpm)
0	3150
600	2400
1200	1714
1800	1200
2400	800
3000	425
3600	0

The speed change during the retardation test was uniform which improves the identification of the moment of the inertia. The slope of retardation curve was obtained from the graph in Figure 7 and found to be 818.25 rpm/s. The moment of inertia was calculated to be 0.00099 kgm^2 using (11) [22].

$$J = \frac{3600P_m}{4\pi^2 N\frac{dn}{dt}} \quad (11)$$

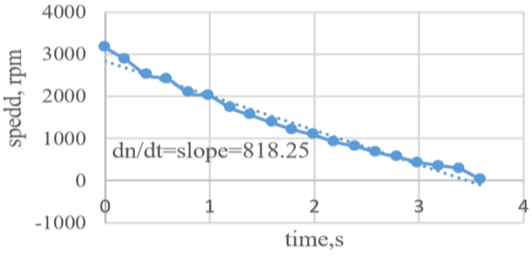


Figure 7. Motor speed versus time

4. RESULTS AND DISCUSSION

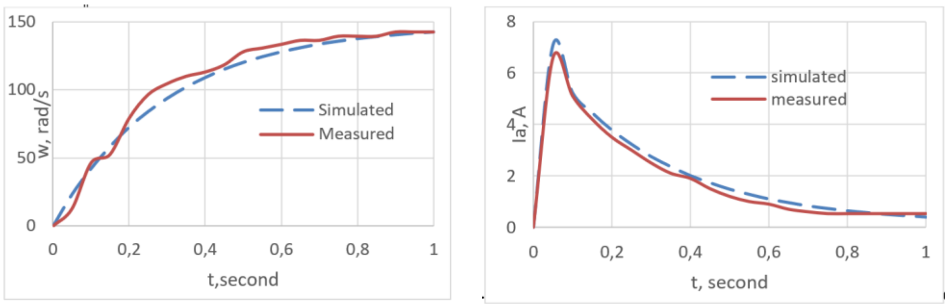
All identified parameters of PMDC motor in section 3 are presented in Table 6. The identified parameters are expressed in terms of electrical and mechanical units. Using the speed and current responses, the identified parameters were used to model the PMDC motor. The identified parameters were substituted in the model that has been derived in Figure 2.

Table 6. Identified parameters of PMDC motor

No.	Paramater	Value
1	Armature resistance, R_a	1.375 Ω
2	Armature inductance, L_a	298.75 uH
3	Back EMF constant, K_e	0.0662 V/rad/s
4	Torque constant, K_t	0.0674 Nm/A
5	Viscous friction coefficient, D	0.00007
6	Moment of inertia, J	0.00099 kgm^2

4.1. Speed and current responses

The open loop speed and current responses can be simulated in MATLAB/Simulink to better understand and compare the simulated model response to the response of the actual motor [23], [24]. A step input voltage with 10 V amplitude is given to the motor. The simulated and actual motor responses are plotted in Figure 8. In Figure 8(a), the motor enters a transient period before settling to its steady state speed after 1 second. The final steady state angular speed is at 147 rad/s. The blue curve shows the simulated step response while the red curve shows the actual motor response. We can see some small difference between the simulated and the actual responses and the trajectory is almost identical and close to real measurement. On the other hand, the simulated and actual current responses using the identified parameter values are plotted in Figure 8(b). Initially, the applied step input voltage is more than the back emf voltage of the motor, there is a surge increase in the armature current to produce a torque to accelerate the motor [25]. After a short time, the back emf voltage is developed and the armature current starts to fall until it reaches a final steady state value at 0.53A. As the motor speed depends on the increased in back emf voltage, the armature current magnitude depends on the difference between the back emf voltage and the applied armature voltage. When the motor speed begins to climb up to a steady state value, the back emf voltage also rises up. Hence, the difference between them is small resulting in the armature current to decay exponentially. According to Figure 8(b), the measured curve from the dynamic transient test is close to the simulation curve.



(a) (b)

Figure 8. PMDC motor responses (a) angular speed and (b) armature current

5. CONCLUSION

In this paper, PMDC motor parameters were identified by doing several experiments in dynamic and steady-state conditions considering no load and transient tests. A PMDC motor for e-bike is modelled and developed for simulation using MATLAB/Simulink software using the identified parameters obtained from experiments and tests. The analysis and performance evaluation of the developed PMDC motor model show that the simulated speed and current responses are close to the actual measurement which has proven the motor parameters were correctly identified and the proposed experiments are very effective in identifying the model parameters. Since the results achieved are based on motor operation on no-load, for future work the experiments may be extendedly tested with a mechanical load attached to the motor to study the speed and the armature current responses.

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